WL-TR-97-2084

ADVANCED FUEL DEVELOPMENT AND FUEL COMBUSTION

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FINAL REPORT FOR 06/01/92-06/01/97

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This technical report has been reviewed and is approved for publication.

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This final report summarizes the efforts performed over the last five years on Contract F33615-92-C-2218. This report represents a collection of research programs, varying broadly in size and complexity with many authors and principal investigators. The objective of this task order contract was to support long-term basic and applied research for problems related to aviation turbine fuels and related materials and combustion of these fuels in advanced systems. Some research and development efforts aimed at evaluating advanced lubricants and lubrication systems were also performed in this contract.

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FOREWORD

This report was prepared by the Environmental Science and Engineering Group of the University of Dayton Research Institute, Dayton, Ohio. It represents a collection of research programs, varying broadly in size and complexity with many authors and principal investigators. The tasks associated with this contract, numbered from Task 1 to Task 26 are summarized in this final report. Each individual task may have associated with it a final report which may be a University of Dayton report, an Air Force Technical Report, a subcontractor report, or merely compilations of technical information. This report, along with its attachments and associated technical reports described all of the work conducted under the subject contract.

This effort was performed under contract F33615-92-2218 for the Fuels Research Group (WL/POSF) of the Aero Propulsion and Power Directorate of Wright Laboratory, Air Force Materiel Command. The authors wish to acknowledge the efforts of Ms. Ellen Strobel, who was the project's technical monitor throughout the length of the contract. Her technical and administrative direction was essential in the successful completion of this very complex task order contract.

The authors also wish to acknowledge the efforts of members of the University of Dayton who were principal investigators and senior researchers, for various tasks in the contract: Dr. Philip Taylor, Mr. Wayne Rubey, Mr. Richard Striebich, Mr. Robert Kauffman, Mr. J. Douglas Wolf, Dr. Peter Hovey, Dr. Yi Pan, Mr. Richard Neumann, Mr. Richard Lewis and others. We also recognize the efforts of the investigators from other subcontracted studies. Finally, we commend the Contracts and Grants Administration staff (Ms. Claudette Groeber, Ms. Carol Eckley and Ms. Diane Brademeyer) for their efforts in procuring and handling 26 separate internal and external research tasks.

1. INTRODUCTION

This final report summarizes the efforts performed over the last 5 years on Contract F33615-92-2218. The objective of this task order contract was to support long-term basic and applied research for problems related to aviation turbine fuels and related materials and combustion of these fuels in advanced systems. Some research and development efforts aimed at evaluating advanced lubricants and lubrication systems were also performed in this contract.

As the Air Force moves into the 21st century, more efficient, higher performance turbine engines are being conceptualized and developed under programs such as the IHPTET initiative. Because efficiency and performance gains can be obtained by increasing temperature and pressure in the engine, higher heat loads are being generated. Since ram air is no longer an effective coolant at higher speeds, the fuel must be used to provide cooling to the engine and airframe.The fuel must be able to accept much greater heat loads than it now typically accepts, (Figure 1) not only for the advanced fighter, but especially in the case of hypersonic aircraft. Indeed, high heat sink fuels are one of the critical "enabling technologies" for high mach aircraft.

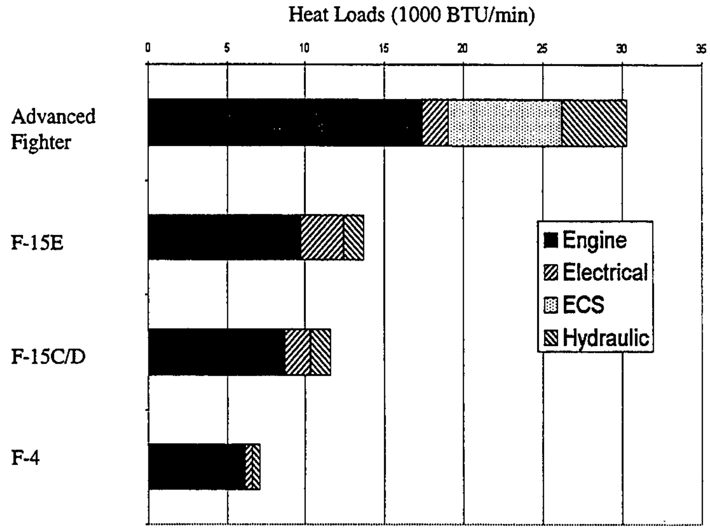

Figure 1. Fuel Heat Loads of Current and Advanced Fighter Aircraft.

For the near term, the higher heat loads required by current aircraft systems such as the F22 are being met by JP-8+100. By using an additive package to extend the thermal stability of JP-8 to 425°C, the Air Force has gained a 50% increase in heat sink, reduced fuel system maintenance, and improved the performance of nozzles, manifolds and fuel controls. In addition, the improvements in soot (signature) and unburned hydrocarbon emissions (environmental pollution) due to better nozzle spray patterns are additional benefits from using JP-8+100. Performance and cost savings due to decreased maintenance and lower emissions need to be continually quantified and documented to demonstrate the cost effectiveness of the additive.

Some of the later tasks performed under this contract specifically addressed development and evaluation of fuel additives aimed at meeting those needs. A description of all tasks performed is presented in Section 2 of this report.

2. TASK DESCRIPTIONS AND SUMMARIES OF RESULTS

The following sections are brief descriptions of the tasks assigned under this program. These descriptions include information about the principal investigator and their affiliation, the program budget, the program duration and other general information about the task. The descriptions include brief summaries of the product of the tasks, which may be a research finding, the development of an instrumentation system or literature review. In many tasks, there were reports and information technical information generated as a result of this effort. These reports are cited whenever possible. The task numbers follow logical, numerical order.

TASK NO. 01: The Role of Gums in Deposit Formation

PERIOD OF PERFORMANCE: May 1992 - August 1993

DOLLAR AMOUNT: $154,000

U.D. PRINCIPAL INVESTIGATOR: Philip H. Taylor

BRIEF DESCRIPTION:

The increasing importance of the thermal stability of aircraft fuels is widely recognized. Of particular interest has been the formation of deposits, consisting of insoluble gums and sediments, that can foul nozzles and fuel lines. In this study we have addressed several issues that appear to be common to most research studies concerning deposit formation. Specific output of this program included: 1) formulation of reaction schemes and kinetic models that can be used to interpret the results of fuel thermal degradation studies; 2) development of a methodology for determination of the rate of reaction of dissolved oxygen; 3) development of GC-MS analytical techniques for measurement of impurities and reaction products; 4) development of supercritical fluid extraction techniques for gums and deposits; 5) generation of homogeneous, liquid phase kinetic data on the consumption of reactants and the formation of reaction intermediates in thermally stressed fuels; 6) development of a technique to determine the rate coefficient and equilibrium coefficient for adsorption of fuel, impurities, oxygen, and reaction intermediates on various surfaces; and 7) advancement of a potentially useful approach to the study of fuel deposit formation.

TASK NO. 02: Advanced Lubricant Segregation Capability for Oil Recycling

PERIOD OF PERFORMANCE: October 1992 - February 1994)

DOLLAR AMOUNT: $200,000

U.D. PRINCIPAL INVESTIGATOR: Robert E. Kauffman

BRIEF DESCRIPTION:

The Air Force historically has collected used lubricating oils for recycling and reuse in secondary markets. Present markets for synthetic ester lubricants include their use as a plasticizer or as heating fuel. However, for maximum environmental protectiveness, it is desired to process used synthetic ester lubricants for reuse at their original purpose. Studies performed for the Air Force have shown that used oils collected at central collection stations can easily be contaminated by personnel improperly disposing of other materials such as mineral oil lubricants, silicone oils, hydraulic fluids, or even halogenated solvents. The presence of halogens in waste oils severely impacts their acceptability as plasticizers or waste-derived fuels. However, the intent to truly reuse these materials for their original purpose (i.e., as synthetic ester lubricants) requires screening for a wide range of contaminant types. The University of Dayton has developed procedures and techniques to control and screen the used oils at the collection point to ensure that collected materials meet specifications required for the specific recycle market chosen.

TASK NO. 03: Emissions Control Through Advanced Combustor Mixing Schemes

PERIOD OF PERFORMANCE: April 1993 - November 1993

DOLLAR AMOUNT: $114,873

SUBCONTRACTOR: University of California, Irvine

SUBCONTRACT PRINCIPAL INVESTIGATOR: G. S. Samuelsen

BRIEF DESCRIPTION:

The reduction of gaseous and pollutant emissions from gas turbine engines requires the understanding of the formation of the pollutants within the combustor. Heretofore, the understanding has been limited due to the inability to measure the relevant variables within the combustor. Recent advances in the evolution of laser diagnostics and the development of model combustors with optical access are providing the opportunity to acquire the needed information. These capabilities notwithstanding, four additional tools are required. Under a prior USAF contract, the University of California Irvine (UC) has developed the following tools:

- First, a high temperature and high pressure facility has been designed, constructed, and successfully operated to 10 atmospheres and 800°F. The facility has full optical access and is fully traversing.

- Second, methods have been successfully developed to measure temperature in situ using coherent anti-Stokes Raman Scattering (CARS) in a model combustor, and in the presence of droplets that one encounters in the dome region of practical combustors.

- Third, a model can combustor that uses common combustor design features and materials has been designed, built by a combustor manufacturer, and tested.

- Fourth, an optical technique (Degenerate Four-Wave Mixing, DFWM) is under development in collaboration with the Sandia National Livermore Laboratory for the non-intrusive ppm measurement of NO and NO_2. Measurements to 10 ppm have been made in flame environments with first combustor tests planned for this summer. While not in a position for use in this particular task, it is expected that the capability will be available for testing in a subsequent task in the event the program is funded beyond the present task.

In addition, two modeling resources have been developed during the prior program. The first is a statistical model for the design of the experiments. The second is a comprehensive numerical code for the interpretation of the data, and to insure that the database developed under the current program will satisfy the needs for industry in the verification and development of their in-house codes.

The technical approach taken was to (1) utilize practical annular combustor and a model laboratory analog; (2) operate and compare the performance of both combustors at a baseline condition, and then conduct a parametric study in the model combustor under practical operating conditions with practical fuels; (3) apply nonintrusive laser diagnostics for the spatially-resolved measurements of key properties in the two-phase flow including droplet size statistics, droplet velocity statistics, radiative flux, gas velocity statistics, and gas temperature statistics; (4) apply statistical modeling for the design of the experiments; (5) identify the relationship between primary wall jet injection and the mixing processes in the dome, and (6) relate these mixing processes to the formation of nitrogen oxides.

The research goals of this task were (1) to establish the functional dependence of the formation of nitric oxide and nitrogen dioxide in gas turbine combustion on the operating and design characteristics of both can and annular combustor designs; (2) to delineate the mechanisms of the formation and emission of nitric oxide and nitrogen dioxide in gas turbine can and annular combustors, and (3) to provide a database from which numerical codes can be developed and verified for the prediction of nitrogen oxides emission. Reference velocities were varied from 7.5 to 20 m/s, air preheat from 72 to 800°F, overall equivalence ratio from 0.3 to 0.5, and pressure from 1.0 to 10.0 atm. Measurements were taken to establish, via parametric variation, (1) the regions and bounds of nitric oxide formation and nitrogen dioxide formation, and (2) the data necessary to produce a hypothesis, in combination with numerical analysis, for the dominant controlling mechanism (or mechanisms) of the physical chemical processes responsible for the formation of nitrogen oxides in gas turbine combustors.

Results of the study included:

- An <u>understanding</u> derived from the experimental data for the dominant, controlling physical processes responsible for the effect of wall jet interaction on the formation of nitrogen oxides in gas turbine combustors.
- Guidelines for the design of combustors and atomizers that minimize the production of nitrogen oxides.
- An <u>experimental database</u> for numerical code development and verification.

TASK NO. 04: Gas Layer Protection of Hot Carbon Structural Materials

PERIOD OF PERFORMANCE: May 1993 - March 1994

DOLLAR AMOUNT: $75,000

U.D. PRINCIPAL INVESTIGATOR: Philip H. Taylor

BRIEF DESCRIPTION:

If combustors and turbine sections of gas turbine engines could be operated at near-stoichiometric combustion conditions, engine efficiency would be significantly improved and specific fuel consumption would be significantly lowered. One of the major obstacles to achieving stoichiometric combustion is that current engine structural materials, i.e., nickel and cobalt-based alloys, lack the thermal stability to be operated at or near adiabatic flame temperatures. Carbon-carbon (C-C) composites can bear the structural loads at stoichiometric combustion temperatures of hydrocarbon-based fuels, but suffer unacceptable mass losses in the presence of oxygen, carbon dioxide, and water vapor. Mass loss occurs essentially because C-C acts as a solid fuel, competing chemically with the fuel for the available oxidizing species. This study has explored the feasibility of protecting hot carbon surfaces from oxidizing environments by exposure to a layer of gases with which the carbon is in chemical equilibrium. These experiments were guided by thermodynamic equilibrium calculations which indicated that, at temperatures in excess of 700°C, carbon monoxide (CO), nitrogen (N_2) and hydrogen (H_2) are the three major species in equilibrium with the carbon surface. The objective of this task was to perform experimental studies of the behavior of heated graphite and C-C specimens upon exposure to oxidizing and protective gas streams of documented chemical compositions. Preliminary results in a chemically reaction kinetic controlled environment did not achieve the desired results. Further experiments in a diffusion-controlled environment are warranted.

TASK NO. 05: Development of an Environmentally Safe, Non-Toxic Icing Inhibitor

PERIOD OF PERFORMANCE: May 1993 - November 1993

DOLLAR AMOUNT: $10,000

U.D. PRINCIPAL INVESTIGATOR: Peter Hovey

BRIEF DESCRIPTION:

Chemical graph theory provides numerical descriptions of chemical structure that are useful for prediction modeling. The numerical descriptions of chemical structure provided by chemical graph theory are based on topological indexes of molecular graphs. The topological indexes measure the information content, size and complexity of the structure of the chemical. Five general types of indexes are: (a) measures of the information content of the structure, (b) simple path, cluster, path-cluster and chain connectivity indexes, (c) bond corrected path, cluster, path-cluster and chain connectivity indexes, (d) valence corrected path, cluster, path-cluster and chain connectivity indexes, and (e) measures based on a collection of low-order path lengths.

The information content and the simple connectivity indexes are measures of the complexity of the structure. The bond corrections take into account aromatic, double and triple bounds while the valence corrections adjust for the valency of the atoms in the structure.

This effort was the first step in a larger program to develop an environmentally safe fuel system icing inhibitor (FHII). The current FHII is drained from the fuel tank along with the bottom water, but cannot be released into sewer or ground water systems. The cost of treating and disposing of the FSII contaminated bottom water is very high so that an environmentally benign FSII could save the Air Force several millions of dollars a year.

This task was aimed at developing a preliminary model relating the chemical structure of the FSII with its performance using chemical graph theory. The preliminary model could be used to demonstrate the feasibility of using chemical graph theory models to help design an environmentally safe fuel system icing inhibitor. The main part of the task was performing a literature search for previous modeling approaches and for existing data on FSII performance and toxicity.

A brief report in the form of an annotated bibliography summarized past modeling efforts for FSII. The data that are available on FSII performance and toxicity were compiled in a database.

TASK NO. 06: Testing and Evaluation of Thermal EHD Software

PERIOD OF PERFORMANCE: June 1993 - November 1993

DOLLAR AMOUNT: $26,028

SUBCONTRACTOR: Purdue Research Foundation

SUBCONTRACT PRINCIPAL INVESTIGATOR:

BRIEF DESCRIPTION:

A program was needed to test and evaluate an elastohydrodynamic (EHD) lubrication model of circular and noncircular tribological contacts and to upgrade a Silicon Graphics® computer. Under a research program sponsored by WL/POSL, researchers at the Purdue Research Foundation developed a computer aided design/graphics (CADG) model to provide user friendly environment to investigate lubricated circular and noncircular contacts. The CADG model allows the user to input the operational parameters by pictorial interactive events. After an EHD analysis has been completed, the model allows the user to examine and interrogate the output results graphically. The user can then view the results in color contour or solid models from any angle or position.

The computer EHD model developed under the WL/POSL sponsored program requires simultaneous solution of the two-dimensional Reynold's, elasticity, and three-dimensional energy equations. The current CADG model provides a state-of-the-art environment to examine the results. However, the model had not been tested and evaluated under a wide variety of operating conditions. Therefore, a testing program for the CADG model under various operating conditions, from low to high in load and speed, and for several types of lubricants and systems materials was required. The specific goals of this task were to evaluate the CADG model under a range of operating conditions with several materials and to upgrade a Silicon Graphics®.

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TASK NO. 07: Alternate Lubricant Gear Load Carrying Evaluation Technique

PERIOD OF PERFORMANCE: June 1993 to March 1995

DOLLAR AMOUNT: $55,570

SUBCONTRACTOR: UEC Tribology Lab

SUBCONTRACT PRINCIPAL INVESTIGATOR: Ron Jeroski

BRIEF DESCRIPTION:

Turbine engine lubricating oils, such as MIL-L-7808 and MIL-L-23699, are required to undergo numerous evaluations to assure production lots are accepted for delivery. One of these important performance characteristics is the capability of the lubricating oil to carry sufficient loads in rotating gears at operating temperature. The load carrying capacity of a lubricating oil is normally defined as the maximum load that the gear tooth face can carry without excessive scuffing. This is obviously an essential lubricant property since excessive scuffing can lead to excessive wear and ultimate component failure. The load carrying capacity of a lubricating oil is a function of its viscosity and chemical composition. The viscosity of the lubricating oil determines its hydrodynamic and elastohydrodynamic performance characteristics in both gears and bearings. The chemistry of the oil and especially of the oil additives can impart a significant influence on load carrying capacity in heavily loaded gears where boundary lubrication becomes more predominant than elastohydrodynamic lubrication.

Up until the present, the technique most utilized to measure the load carrying capacity of aircraft turbine engine lubricating oils has been the Ryder Gear Test as described in ASTM D-1947. However, this test has recently become unavailable for use because of a loss of an acceptable source of supply for the test gears. The two acceptable test gear manufacturers have ceased production. Although extensive efforts have been made and are continuing to find acceptable alternative manufacturing sources, none have been successful to date. Thus, the purpose of this task was to determine the applicability of the FZG Four-Square Gear Test as an acceptable alternative for the Ryder Gear Test.

UDRI identified UEC Tribology Labs as the only firm capable of performing the FZG Four-Square Gear Test in a timely fashion. UDRI engaged the services of UEC as a subcontractor willing to perform the tests at a predetermined price per sample for up to 40 samples. Samples were sent by the Air Force to UEC where they were subjected to the following test regimen.

Tests were performed using the FZG Four-Square Gear Test Method (S-70). The tests were run at 1760 RPM using the 15-minute step load procedure until failure or step load 12 maximum, whichever occurred first.

The following criteria were followed for each test:

(a) A visual rating of percent scuff on each tooth and total percent scuff was performed after each load step on the pinion gear.

(b) Until a change is noted, visual ratings were made on the lower load steps. After either a load change, or load step 6 was completed, a measurement of weight loss for each gear and gear set was performed after every other load step.

(c) Additional weighing of the gears was performed as warranted.

(d) Polaroid pictures of gears were supplied for each load step after scuffing occurred.

(e) Spectrographic analyses for metals were performed after each load step. Wear debris analyses were performed after failure or 12 load steps.

A status report for each test performed was prepared and sent to UDRI and the Air Force, describing the performance of each lubricant investigated using the FZG Four-Square Gear Test.

TASK NO. 08: Thermal Gradient Programmed Gas Chromatography

CONTRACT OR GRANT NO: F33615-92-C-2218 - Task 08

PERIOD OF PERFORMANCE: June 1993 - June 1994

DOLLAR AMOUNT: $47,000

U.D. PRINCIPAL INVESTIGATOR: Wayne A. Rubey

BRIEF DESCRIPTION:

Classically, the detailed chemical characterization of gas turbine engine lubricants has been accomplished largely through the use of chromatographic and spectroscopic procedures. Turbine engine lubricants of the future will be exposed to significantly more severe environments. A variety of different high-temperature lubricant compounds and formulations are under investigation as candidates to meet this need.

However, the ability to analyze and study those lubricants currently in use, and various candidate lubricants which are intended for high-temperature exposures require advanced instrumental analysis techniques. Detailed analysis capabilities will be required for full lubricant. In addition, rapid measurement techniques will be needed for: tracking lubricant degradation, monitoring for impurities, storage testing, conducting in-line pyrolyses of nonvolatiles, screening of samples via simulated distillation, checking the status of incorporated additive packages, and analyzing oxidative and pyrolysis products formed in both the condensed and vapor phase. These analytical requirements can be fulfilled by a new gas chromatographic operational mode that has recently been introduced by the University referred to as thermal gradient programmed gas chromatography (TGPGC).

A thermal gradient programmed gas chromatography-experimental apparatus (TGPGC-EA) has been assembled at the University of Dayton. This experiment apparatus provided the specific guidance information with respect to the design of hardware and components needed for implementing appropriate high-temperature TGPGC procedures.

Design work and associated experiments were conducted using different modes of CSA heating and cooling. Although convection heating has been the primary heat transfer procedure employed thus far, investigations will also address electrical resistance heating, thermal conduction, and radiant energy heat transfer.

A vortex cooler and heater was evaluated and metal OTCs were selected for evaluation. The results of the study were presented at the 16th Internal Symposium on Capillary Chromatography at Riva del Garda, Italy in September 1994.

TASK NO. 09: Assessment of the Friction Characteristics and Scuffing Potential of a Helicopter Transmission Lubricant

PERIOD OF PERFORMANCE: August 1993 - December 1993

DOLLAR AMOUNT: $20,828

SUBCONTRACTOR: Wedeven Associates

SUBCONTRACT PRINCIPAL INVESTIGATOR: Laverne Wedeven

BRIEF DESCRIPTION:

Military Specification DOD-L-85734 helicopter gearbox lubricants are used throughout the Department of Defense for all helicopter transmission drive systems. Lubricants meeting this specification demonstrate improved capacity in reducing premature failures due to gear scuffing, premature wear or bearing surface distress in service. The improved performance of these oils is due to additive components which activate under conditions where boundary lubrication is dominant. These chemicals react with the adjacent metal surfaces under the extreme conditions of contact and provide the added surface protection observed. Surface distress occurs when the contact loads and temperatures exceed the capabilities of the chemical films present, with component failure following shortly thereafter.

Gear testing is the conventional methodology used to assess the load carrying capacity of the DOD-L-85734 oils. This test, described by ASTM Method D-1947, defines the maximum load at which a test gear experiences gross surface distress, as evidenced by excessive gear "scuff." Little information is known of the frictional behavior of oils under the severe conditions leading up to, and just prior to, complete surface distress. The effects of loading sequence, contact velocities and surface finish on these parameters is also not well defined. The purpose of this task was to determine the frictional/tractive behavior of a reference lubricant and a DOD-L-85734 oil in a ball-on-disk test device.

Since standard methods (gear testing using ASTM D-1947) for determining the friction characteristics of lubricants do not fully describe frictional behavior of lubricants under all conditions of interest, Wedeven Associates has developed a unique new methodology to further the knowledge of lubricant behavior under actual operating conditions. This technique allows a determination of frictional behavior of lubricants under other than complete surface stress. Testing of Air Force supplied oils was performed using the Wedevan Associates Machine number 3 (WAM3) to investigate the frictional/tractive characteristics of two lubricants.

During the course of testing, it was discovered that the two DOD-L-85734 aviation oils were very peculiarly different. This was a surprising fact, different from what is currently known about these oils. Additional testing was required to confirm and explain these differences as required by the technical intent of the contract. To accomplish this, test rig modifications and calibrations were required to be made, and the total number of tests required to explain the results had to be increased by more than a factor of two. A task report entitled, "Assessment of

the Friction Characteristics and Scuffing Performance of DOD-L-85734 Oils" was prepared and submitted to the Air Force.

TASK NOS. 10 AND 10A: Test Instrumentation for the NASP Program

PERIOD OF PERFORMANCE: November 1993 - May 1994 (Task 10)

June 1994 0 December 1994 (Task 10A)

DOLLAR AMOUNT: $49,340 (Task 10); $51,140 (Task 10A)

U. D. PRINCIPAL INVESTIGATOR: Richard Neumann

BRIEF DESCRIPTION:

A UDRI researcher was assigned to the NASP Program Office to conduct studies concerning high temperature thermal, pressure and acoustic instrumentation techniques. The aim of this effort was to recommend feasible technical approaches in instrumentation selection, development and application. The international technical literature was reviewed so as to minimize duplication and parallel development efforts. UDRI supported NASP engineers with critiques of possible new instrumentation techniques and consolidated and documented the status of NASP instrumentation as required presenting this documentation at appropriate levels within the NASP program.

UDRI staff also critiqued the appropriateness and possible problems connected with the use of thermal instrumentation in tests for systems development and CFD validation. Experimentation from the Wright Laboratory Mach 6 facility which validates flowpath thermal instrumentation was documented and the application of that instrumentation to complex flowpath problems was analyzed. The products of NASP-funded instrumentation efforts assuring accurate effort, documentation, and general technical applicability to other Air Force programs were consolidated and documentation of NASP instrumentation efforts within the NASP program was prepared.

The intent of this task was to prepare a state-of-the-art review of thermal instrumentation applied to convective heating problems in high speed wind tunnel facilities. Under this task, a review paper on thermal instrumentation was prepared. While some of the material was developed by the PI, most of the information contained herein is derived from a worldwide technical effort in thermal instrumentation. In all cases, special efforts were taken to credit the author of record. In most cases, only the highlights and conclusions of that author's work have been presented in the paper. The goal of this work was to develop, under one cover, a comprehensive body of information on the wide variety of thermal instruments available today and to give the reader ample references such that additional study can be conducted using the source papers of the developing author.

The subject of thermal instrumentation is currently a worldwide research activity spurred by a growing interest in hypersonics and fueled by scientific advances in such diverse subjects as micro-machining; chemistry and electronic chip production. No review of the type prepared in this task would be valid or comprehensive without a worldwide perspective on ideas and advances. The report endeavored to present that worldwide perspective based on the output of

international symposia; international journals and personal contacts. It must be stated in all candor that U.S. researchers are not generally aware of the bulk of international research because we don't subscribe to the international journals in which this material is reported or understand what has already been accomplished. That false economy on the part of U.S. research organizations can lead to expensive and incorrect conclusions and the expenditure of unnecessary test costs to either circumvent a problem already solved elsewhere or to re-invent instrumentation currently used elsewhere.

TASK NO. 11: Peer Review of Fuels and Lubrication Division In-House Technology Program

PERIOD OF PERFORMANCE: November 1993 - February 1994

DOLLAR AMOUNT: $29,002

U. D. PRINCIPAL INVESTIGATOR: Joseph T. Swartzbaugh

BRIEF DESCRIPTION:

Because the Wright Laboratory Chief Scientist requested that an external peer review of the quality of in-house technology efforts be conducted within the next three months, UDRI was asked to organize the external review. Three technical areas were identified within the Fuels and Lubrication Division for review:

(a) Air Breathing Propulsion Fuels

(b) Fuel Combustion and Diagnostics

(c) Turbine Engine Lubricants and Associated Mechanical Subsystems

Three prospective reviewers were identified for each of the above areas. Candidate reviewers contacted to assess their interest and availability in performing the review. Acceptable candidates were told that the review required their presence at Wright-Patterson AFB for approximately 2 days.

Because some UDRI personnel were active participants in some of the research under review, the University divorced itself from active participation in the actual reviews. Thus, the University performed this task through subcontracted expert reviewers and no University personnel were directly involved in the reviews nor were any University personnel privy to any of the investment strategy information identified in the Task Assignment Request.

Working in concert with Air Force personnel, the University staff identified candidate reviewers to perform the required peer review activities. Upon approval of these candidates, the University contacted those candidates and arranged for their travel to WPAFB for their participation in the 2-day peer review team meetings.

The review meeting for Air Breathing Propulsion Fuels topic area engaged the following peer reviewers:

- Mr. Glen Harper, McDonnell Douglas Corp.
- Dr. William Taylor, Exxon Research and Engineering Co.
- Dr. George Mushrush, George Mason University

The review meeting for the Fuel Combustion and Diagnostics topic area engaged the following experts for the review team:

- Mr. Stanley Mosier, Private Consultant
- Prof. A. M. Mellor, Vanderbilt University
- Dr. Edward Mularz, NASA Lewis Research Center

The review meeting for the Turbine Engine Lubricants and Associated Mechanical Subsystems topic area utilized the following experts for the peer review team:

- Mr. Jorge A. Alcorta, Pratt and Whitney Aircraft
- Prof. Bernard Hamrock, Ohio State University
- Dr. James Dill, Mechanical Technology, Inc.

Reviewers attended their scheduled on-site review at WPAFB. The reviewers evaluated the quality of the in-house research conducted by Air Force personnel. Reviewers were exposed to the technical area's technology strategy and the context (externally funded contracts and on-site contracted research) of the in-house research but did not evaluate investment strategy. The review teams provided oral briefings to the Air Force presenters and an exit interview to the Directorate Associate Chief Scientist at the conclusion of their 2-day review. The review team also provided a written report of findings and recommendations to the Directorate Associate Chief Scientist.

TASK NO. 12: High Temperature Bearing Material Wear Evaluation

PERIOD OF PERFORMANCE: April 1994 - June 1994

DOLLAR AMOUNT: $32,623

SUBCONTRACTOR: Wedeven Associates

SUBCONTRACT PRINCIPAL INVESTIGATOR: Laverne Wedeven

BRIEF DESCRIPTION:

One IHPTET Phase II hybrid bearing design will most likely utilize silicon nitride rolling elements and Pyrowear 675 for other components. Government programs underway at the time of this task conducted bearing tests with these materials. Previous abrasive wear tests under sliding conditions representing the cage/land interface for Pyrowear 675 generated concern regarding wear behavior.

Therefore, the objective of this task was to first assess the wear performance of Pyrowear 675 relative to M50 NiL baseline materials using Skylube 600 as the baseline lubricant. Secondly, the wear performance of Si_3N_4/Pyrowear 675 hybrid material was assessed relative to all steel Pyrowear 675 material with Skylube 600. The tribological performances of an all steel Pyrowear 675 material and hybrid material pairs were then assessed using MCS2482. Tribological tests of these materials included performance evaluation compared with conventional MIL-L-7808 oil.

Evaluations were conducted with unique test methodologies designed specifically for high temperature bearing materials and lubricants. These tests included elevated temperature wear tests and load carrying capacity (newly developed for U.S. Navy for oil qualification - MIL-L-223699 specification). Ball and disc specimens were used in two Wedeven Associates, Inc. test machines, WAM1 and WAM3.

One Pyrowear 675 disc was furnished by the government. Both top and bottom surfaces of the disc were used and refinished several times to allow a sufficient number of tests. Pyrowear 675 ball blanks (11/16-inch dia.) also were government furnished. The ball size was the same as required for future testing of 6309 size bearings. M50 NiL ball blanks and discs were obtained from SKF-MRC. Silicon nitride ball specimens were available at Wedeven Associates, Inc. Under subtask 12-1, materials were procured and test specimens fabricated.

In subtask 12-2, elevated temperature tests were conducted with rolling/sliding contact under mixed film lubrication conditions. Temperature ranged from 23°C to 360°C, except for MIL-L-7808. Quantitative wear was measured relative to M50 NiL baseline. Tests were conducted with Skylube 600 and MIL-L-8708 oils.

Under subtask 12-3, elevated temperature tests were conducted with rolling/ sliding contact under mixed film lubrication conditions. Temperature ranged from 23°C to 360°C, except for MIL-L-7808. Quantitative wear was measured relative to all-steel Pyrowear 675 from subtask 1. Tests were conducted with Skylube 600 and MIL-L-7808 oils.

Finally, in subtask 12-4, tribological performance included elevated temperature wear tests using MCS2482 as described in subtasks 2 and 3. It also included load carrying capacity tests with MCS2482, Skylube 600, and MIL-L-7808.

TASK NOS. 13 AND 13A: Emissions Control in High Heat Release Burners

PERIOD OF PERFORMANCE: April 1994 - November 1994 (Task 13)

September 1994 - March 1995 (Task 13A)

DOLLAR AMOUNT: $130,033 (Task 13); $99,842 (Task 13A)

SUBCONTRACTOR: University of California, Irvine

SUBCONTRACT PRINCIPAL INVESTIGATOR: G. S. Samuelsen

BRIEF DESCRIPTION:

The objectives of the task were to:

- Identify advanced combustor dome designs that feature reduced variation in local fuel-air mixtures over a wide range of conditions;
- Assess the ability of these designs to maintain high performance while achieving the above;
- Identify promising hardware for additional testing.

To meet these objectives, the following was carried out.

Establish Baseline Geometry. Since advance combustor concepts were to be investigated, the task was planned around a suitable candidate which was provided by General Electric Aircraft Engines. This geometry was evaluated in single cup tests as well as multiple cup tests.

Identify Measurements Required. The important aspects of the mixing which needed to be interrogated was established and the appropriate diagnostic tools identified. The first level of diagnosis permitted relatively rapid screening of general performance attributes. The second level, while more time intensive, provided the details required to understand the physical processes occurring.

Establish Test Plan. A systematic and thorough test plan was established to enable the assessment of the hardware over a range of conditions. Experiments aimed at optimization of geometry and operating attributes (e.g., flow splits) were conducted.

In a follow-on extension to this task, the subcontractor identified advanced combustor dome designs intended to exercise tight control over local variations in the fuel-air ratio over a broad range of fuel flows, and screened these designs for effectiveness in controlling emissions while delivering high performance. Finally, the subcontractor identified promising hardware configurations for full scale testing.

The subcontractor investigated the impact of the primary jets on the performance and emissions associated with sets of optimized swirler/injector/dome configurations. A study was

conducted to optimize the liner jet parameters that gave maximum performance and minimum emissions for the swirler/injector/dome considered. Performance parameters of combustion efficiency and lean-blow-out formed the basis of the primary jet optimization study. Emissions parameters measured were: carbon monoxide (CO), unburned hydrocarbons (UHC), soot, and oxides of nitrogen (NO and NO_2). Both performance parameters and emissions parameters were considered in the primary jet optimization study.

TASK NO. 14: Turbine Engine Oil Recycling - Advanced Lubricant Segregation

PERIOD OF PERFORMANCE: April 1994 - April 1995

DOLLAR AMOUNT: $$249,963

U.D. PRINCIPAL INVESTIGATOR: J. Douglas Wolf

BRIEF DESCRIPTION:

Research conducted in other studies by UDRI found that significant environmental and economic advantages could be obtained by collecting used synthetic lubricants as a separate waste stream and selling them for recycling rather than disposing them by incineration. This study examined this option for other fluids typically used in military applications to determine if similar potential benefits existed for them. The study focused on four fluids: (1) petroleum based oils, (2) glycols, (3) hydraulic fluids, and (4) industrial machining oils. Criteria for recycling of these materials were examined and sensors and screening equipment were developed to assist generators of these waste streams in their collection efforts. The study found that the economic advantages of recycling were not as lucrative for any materials as for the synthetic aircraft engine lubricants. Instruments which could determine the glycol concentration of glycol/water solutions and which could measure electrical conductivity of various fluids were found to have commercial applications.

TASK NO. 15: Turbine Engine Oil Recycling - Feasibility Assessment and Field Demonstration of Prototype Lubricant Segregation Capability

PERIOD OF PERFORMANCE: July 1994 - July 1995

DOLLAR AMOUNT: $247,925

U. D. PRINCIPAL INVESTIGATOR: J. Douglas Wolf

BRIEF DESCRIPTION:

As federal, state, and local regulations regarding waste disposal become more stringent, the need to address current disposal practices for used synthetic aircraft engine lubricants has become an important issue. This study examined recycling as an alternative to commonly-used disposal options. This study focused on the positive economic and environmental issues involved with recycling these materials. Based on input from recycling companies, sensors and screening equipment were developed to assist used oil generators in segregating recyclable oils from other oils and materials that could not be recycled. Prototype collection and recycling programs were developed to examine the impact of recycling used oils on the overall waste disposal programs.

TASK NO. 16 Thermal Decomposition Characterization of Turbine Engine Lubricants and Additives

PERIOD OF PERFORMANCE: May 1994 - October 1994

DOLLAR AMOUNT: $49,989

U. D. PRINCIPAL INVESTIGATORS: Wayne Rubey

BRIEF DESCRIPTION:

Synthetic lubricants are occasionally formulated using trimethylolpropane esters with triarylphosphate as an additive. When subjected to high temperatures (350-700°C), these materials have been shown to form a neurotoxin, trimethylolpropane phosphate (TMPP) (Kalman 1985; Callahan 1989). Lubrication engineers have discussed the history and significance of this concern (Centers 1992) and advise against uninformed, inadvertent, or unprotected use of these lubricants in a high-temperature environment. Indeed, the high temperatures may be generated by means of waste oil combustion or may be generated in an inappropriate lubricant application (Havenga 1994).

As a pollution prevention measure, the armed services, and the Air Force in particular, are investigating the disposal of used Petroleum, Oil, and Lubricants (POL) by using it as, or in addition to, a boiler fuel. As some of these POL mixtures may contain the necessary reactants to form TMPP, a study was conducted under this task at Wright Laboratory (Tyndall Air Force Base, Florida) to analyze for TMPP in the gaseous combustion effluent of a boiler system burning synthetic lubricants mixed with diesel fuel.

The high-temperature combustion of synthetic ester turbine engine lubricants has been performed by diluting the lubricant 5, 15, or 25% in diesel fuel and burning the mixture in a pilot-scale boiler facility. The effluent gas from this combustion system was carefully monitored for the formation of a potent neurotoxin, trimethylolpropane phosphate (TMPP). Although TMPP was not detected in the gaseous effluent, elevated levels of the neurotoxin were found in scrapings from the inside of the boiler system. Because of the extreme toxicity of this compound, significant dermal exposure could be a potential risk to incinerator operation and maintenance personnel.

TASK NOS. 17 AND 17A: High Temperature Test Instrumentation

PERIOD OF PERFORMANCE: August 1994 - December 1994 (Task 17)

September 1994 - October 1994 (Task 17A)

DOLLAR AMOUNT: $55,000 (Task 17); $6,385 (Task 17A)

U. D. PRINCIPAL INVESTIGATOR: Richard D. Neumann

BRIEF DESCRIPTION:

The intent of this task was to analyze the results of ground test programs conducted in the WL Mach 6 tunnel for the purpose of defining the aerothermodynamics of engine related shock/boundary layer interactions. UDRI staff produced practical design oriented methodology defining the increase of heat transfer caused by these phenomena and documented the results of these tests and their analysis in a technical document for use by engineers on the NASP program.

A UDRI researcher analyzed the results of cowl/sidewall experiments conducted in the WL Mach 6 tunnel for the purpose of defining the aerothermodynamics of engine related shock/boundary layer interactions. He then generalized the results in terms of design-relevant parameters suitable over a wide range of flow conditions for use on SSTO and HyStp studies. Finally, he initiated practical design oriented methodology defining the increase of heat transfer caused by these phenomena.

UDRI staff developed a plan to mitigate the effects of shock interaction observed in the cowl/sidewall model. The plan processed from an understanding of physical phenomena observed in the earlier Mach 6 tunnel experiments using and modifying existing test hardware and selecting the most cost-effective test facilities and test techniques to fully demonstrate reductions in thermal loads to acceptable levels.

In a related effort, a series of wind tunnel tests were performed with the Concept Demonstrator Engine (CDE) inlet for the purpose of understanding the pressures, temperatures, and heat transfer rates occurring in the inlet during normal conditions and situations which caused the inlet to choke or unstart. This data was intended to provide valuable deign information for the development of propulsion systems for high velocity vehicles. In order to provide this guidance, it had to be captured from the large set of data taken during the test program, saved in a form usable by design engineers, and stored in an accessible location. This task was later amended to include efforts designed to capture and preserve that data.

TASK NO. 18: A Real-Time Planner for Dynamic Load Balancing in a Heterogeneous Network of Processors

PERIOD OF PERFORMANCE: October 1994 - October 1995

DOLLAR AMOUNT: $$43,962

U. D. PRINCIPAL INVESTIGATOR: Yi Pan

BRIEF DESCRIPTION:

Since most of real-time scheduling problems in a distributed computer system are known to be NP-hard, an approximation approach that takes heuristic methods using conventional computer algorithms has been used traditionally to solve these scheduling problems. AI planners have been used extensively in manufacturing scheduling and operations research. In this task, the UDRI PI demonstrated the idea of using an AI planner called PRODIGY to perform scheduling through two examples. The first problem was to schedule several image tasks on a distributed computer system. The second problem was to schedule task graphs on a distributed computer system. In our first problem, we assumed that there were only three image operations: enhance, detect, and understand to be performed by processors. These three operations were linearly dependent; i.e., enhance operation had to be finished before detect operation and detect operation had to be finished before understand operation. The dependence relations between these tasks were fixed and the operations were linearly dependent. However, such assumptions were not suitable and valid in many situations. To overcome the difficulty here, we also designed and implemented the second domain which was able to schedule a general task graph on a distributed computer system. Here, dependence relations among tasks were described through a graph. Clearly, task graphs were dynamic and flexible for expressing dependence relations. In the implementation, a task graph was specified as part of input to the PRODIGY system, thus allowing flexibility in the domain. A task report was prepared which presented the domain theory and problem specification for both problems through PRODIGY description language PDL. Operators and inference rules used to implement these two domains were described in detail. Future research direction was identified and several topics to continue this research also were suggested.

TASK NO. 19: Dry Lubrication for Expendable Engines

PERIOD OF PERFORMANCE: July 1995 - January 1996

DOLLAR AMOUNT: $32,600

SUBCONTRACTOR: Desilube Technology

SUBCONTRACTOR PRINCIPAL INVESTIGATOR: James King

BRIEF DESCRIPTION:

Currently some expendable engines use aircraft fuel to lubricate the rolling element bearings. However, alternative approaches will be required to meet higher operating temperatures predicted for future development engines due to fuel thermal stability constraints. Two promising alternative approaches are dry lubrication and carbon-carbon composite bearing cages. The objective of this task was to further explore dry lubrication for application in high temperature/high speed rolling element bearings. The successful development of this technology will reduce thermal loading of the aircraft fuel.

UDRI's subcontractor carried out the following tasks over a period of 6 months.

1. Coated 16 sets of silicon nitride bearing test specimens (64 pieces) with eight solid lubricants -- two sets of each solid lubricant. The eight solid lubricants were $Li_2O{\cdot}SiO_2$, $Na_2O{\cdot}SiO_2$, $K_2O{\cdot}SiO_2$, $Ca_2O{\cdot}SiO_2$, TiO_2, $ReO_2{\cdot}CuO$, CeF_3 (or LaF_3), and CaF_2 (or CaF_2/BaF_2). WL/POSL supplied the test specimens.

2. Prepared and supplied 1.5 lbs of Cs_2WOS_2 to WL/POSL.

3. Obtained fracture toughness data on Si_3N_2 samples with and without $Cs_2O{\cdot}SiO_2$ reaction layer.

4. Summarized all results including fracture toughness data in a short report submitted to WL/POS.

TASK NO. 20: Carbon-Carbon Cages for Expendable Engines

PERIOD OF PERFORMANCE: August 1995 - February 1996

DOLLAR AMOUNT: $33,021

SUBCONTRACTOR: BF Goodrich Aerospace

SUBCONTRACTOR PRINCIPAL INVESTIGATOR: Wei Shih

BRIEF DESCRIPTION:

Currently some expendable engines use the aircraft fuel to lubricate the rolling element bearings. However, alternative approaches will be required to meet higher operating temperatures predicted for future development engines due to fuel thermal stability constraints. Two promising alternative approaches are dry lubrication and carbon-carbon composite bearing cages. The objective of this task was to further explore carbon-carbon material for application in high temperature/high speed rolling element bearings. The successful development of this technology will reduce thermal loading of the aircraft fuel.

UDRI subcontractor BF Goodrich Aerospace fabricated one (1) 2.125" OD x 1.600" ID x 6" long carbon fiber reinforced tube preforms from each of the following three (3) different material concepts:

A	Reinforcement	As-received T300 3k (axial)/6k (braid).
	Construction	3D triaxially braiding. 45% FV targeted.
	Resin	None.
	Curing	CVI rigidization.
	Performance	Balanced strength and modulus in all three (3) directions. High Cost.
B	Reinforcement	Heat stabilized T300 3k.
	Orientation	2D balanced fabric. 55% FV targeted.
	Resin	Phenolic resin.
	Curing	Inflatable metal mandrel and metal mold will be used to apply pressure during 350°F resin curing to ensure sound ply compaction.
	Performance	Good in-plane strength and modulus. Low interlaminar shear and tensile strengths.
C	Reinforcement	Staple PAN fiber.
	Orientation	2D KFB fabric. 30% FV targeted.
	Resin	Phenolic resin.
	Curing	Expandable mandrel will be used to exert pressure during resin curing to ensure sound ply compaction.
	Performance	Adequate in-plane strength with low modulus. Good interlaminar shear and tensile strengths.

The cured preforms were carbonized to about 1500°F in an inert environment and then densified via the Chemical Vapor Infiltration (CVI) process.

TASK NO. 21: Thermal Decomposition Behavior of Triarylphosphates from the Vapor Phase

PERIOD OF PERFORMANCE: August 1995 - February 1996

DOLLAR AMOUNT: $21,991

U. D. PRINCIPAL INVESTIGATOR: Wayne A. Rubey

BRIEF DESCRIPTION:

The high-temperature lubrication of bearing surfaces, such as encountered in advanced gas turbine engines, has been shown to be advantageously accomplished using a vapor-phase lubrication process. Tricresylphosphates and closely related compounds have been shown to possess significant capabilities in temperature regions extending from 300 to almost 700°F.

The chemical constituents which can serve as suitable high-temperature vapor-phase lubricants are quite restricted.

A variety of laboratory studies are underway that are systematically investigating different aspects of the thermal behavior and decomposition properties of these vapor-phase lubricants.

The formation of stable thermal decomposition products is dependent upon many variables, and accordingly, numerous gas-phase studies have been conducted which have identified these different operational parameters. The four major variables are usually: exposure temperature, the mean residence time at high-temperature exposure, the composition of the gaseous atmosphere, and the extent of vapor-phase mixing of components (e.g., organics/air mixing). In the thermal testing of lubricants, the chemical nature of contacted surfaces is also very important.

A specific triaryl phosphate, t-butyl phenyl phosphate (TBPP), is finding increased usage as a high temperature lubricant in the vapor phase. While the performance of TBPP is extremely promising, there is concern about potentially toxic byproducts. The objective of this particular research task was to employ thermal decomposition analysis to identify byproducts of TBPP in the vapor state.

Thermal decomposition experiments were conducted at temperatures ranging from 600 to 900°F. The sample feed was admitted in a continuous manner (Sage syringe pump) and the degradations occurred in a purified flowing air environment.

The collection of effluent was accomplished using a tandem arrangement of porous polymer sorbent traps. These adsorptive devices were carefully selected such that quantitative capture and nondestructive desorptions are accomplished.

Thermal testing was performed at 600, 750, and 900°F. The thermal decomposition testing was performed at Wright Laboratories (Building 490) with the Vapor Dispensing Unit which is located in Room 136. The analyses of the various collected samples was performed using chemical analysis instrumentation located on the campus of the University of Dayton. Specifically, GC-MS instrumentation that is in the Environmental Science and Engineering Laboratory was used for performing these various analyses.

A detailed series of thermal degradation tests with a packed metal thermal reaction were conducted, and the captured effluent products were analyzed by GC-MS.

TASK NOS. 22 AND 22A: Control of NOx in High Heat Release, Low Emission Trapped Vortex Combustors for Gas Turbine Engines and Waste Incinerator Afterburners and Demonstration of Pressure and Temperature-Sensitive Paints for Turbomachining Application

PERIOD OF PERFORMANCE: July 1995 - January 1996 (Task 22)

September 1995 - June 1996 (Task 22A)

DOLLAR AMOUNT: $200,623 (Task 22); $87,721 (Task 22A)

SUBCONTRACTOR: ISSI

SUBCONTRACTOR PRINCIPAL INVESTIGATOR: Dr. Larry Goss

BRIEF DESCRIPTION:

Under an Air Force Strategic Environmental Research and Development Program (SERDP), a combustor design model was used to investigate the performance and NOx emissions characteristics of a Trapped Vortex (TV) combustor. The calculations indicate that the performance of the TV combustor is greater and the construction simpler and less costly than that of other combustor designs. The model studies also indicate that the NOx emissions are considerably lower than those in today's engines.

Trapped Vortex (TV) combustors, while simple in design, exhibit excellent performance characteristics. The extremely low lean blow out and wide turndown ratios demonstrated by TV combustors allow a much wider operational envelope than that possible with traditional combustors. For enhancement of the performance and low-emission characteristics of TV combustors, it is important to understand the design rules for optimizing both the dimensions of the combustor cavity and the fuel and air injection locations. In this task, research efforts will be divided into two parts, corresponding to different applications of TV combustors. Part A of the program dealt with applying TV combustors to gas-turbine engines, while Part B dealt with applying them to waste incineration. In Part A experimental emissions (NOx, unburnt hydrocarbons, and CO) and lean blow-out measurements were made under various flow conditions to address the impact of swirling flow on combustion stability and emission index. In Part B computer modeling of TV combustors will be undertaken, with emphasis on optimization of cavity size for both central and wall-type configurations. The results obtained from these experimental and numerical studies will aid in determining the optimum design features for low-emission, high-performance TV combustors.

In addition, the need in the aerospace community for reliable measurements of surface pressure and temperature is tremendous. The ability to map surface pressures and temperatures nonintrusively with rapid response and virtually limitless spatial resolution would represent a tremendous step forward for the aerodynamic design engineer. In particular, the ability to

capture steady-state and transient pressure and temperature measurements on the surface of a turbomachinery blade to quantify its loading accurately, reliably, and economically would revolutionize the gas-turbine industry. If data acquired using optically active temperature-sensitive coatings could be used to improve film cooling to yield operating temperatures 30°C lower than those that currently exist, a doubling of the life expectancy of a turbine blade would be realized. A number of luminescent materials show great promise for optical determination of pressure and temperature. When these materials are doped into solution and applied to a surface as a paint, pressure and temperature parameters can be measured over that surface.

This task was originally intended to complete parts 1 and 2 below, but was subsequently modified to include parts 3 and 4.

1. Characterization of Trapped-Vortex Performance. Extensive emission measurements were made on different configurations of the trapped-vortex combustor.

2. CFDC-Combustor-Code Development and Application. Time-dependent Computational Fluid Dynamics with Chemistry (CFDC) codes were developed for the study of flame-vortex interactions.

3. Fuel-Thermal-Stability Studies. The thermal stability of jet fuels to be utilized in trapped-vortex combustors was investigated.

4. Pressure-Sensitive-Paint Development and Application. Pressure-sensitive paints were developed and applied to the study of turbo-machinery.

Part 1. Characterization of Trapped-Vortex-Combustor Performance

The performance of the 4-in. trapped-vortex (TV) combustor was characterized through emission and temperature measurements. Emission measurements were made under various operating conditions at atmospheric pressure. The test matrix of the operating conditions was systematically varied for the following flow variables: main air, main equivalence ratio, cavity air, cavity equivalence ratio, and air temperature. Experiments were first conducted over a range of primary equivalence ratios (Φ_p), with the main-air mass flow rate being maintained around 15 lb/min and at an inlet air temperature of 500°F. The combustion efficiency (from cavity combustion alone) was found to maximize around $\Phi_p = 0.7$.

The vortex-cavity operating condition was maintained at $\Phi_p = 0.7$, based on combustion efficiency and reduced NOx, and emission data were collected for a range of overall equivalence ratios (Φ_o) of 0.3 - 1.0 under three constant main-air flows of 9, 12, and 15 lb/min.

The effect of inlet temperature on combustor performance was characterized under conditions of $\Phi_p = 0.7$ and $\Phi_o = 0.6$ at 15 lb/min main-air flow. As expected, the efficiency increased with inlet temperature as a result of the higher heat input to the system. Therefore, the combustor is expected to be highly efficient at the elevated inlet temperatures of real engines.

Temperature profiles were also determined in the exhaust plane of the combustor using a thermocouple rake consisting of nine evenly spaced elements (0.4-in. separation). The temperature profiles were recorded for five different Φ_o's, with a fixed main-air flow of 15 lb/min and $\Phi_p = 0.7$. For each condition, six temperature profiles were obtained in different circumferential directions for evaluating the circumferential variation in temperature distributions.

Part 2. CFDC Code Development and Application

Numerical Simulations of TV Combustor Concepts. Trapped-vortex concepts were studied numerically using a third-order-accurate time-dependent CFDC code. Calculations were made for the cold flow over an afterbody arrangement used by Little and Whipkey to establish the accuracy of the code in predicting the minimum-drag criterion. The bluff body used in this study has a 87.5-mm-diam disk attached to a 100-mm-diam forebody via different-size spindles. A cavity was formed between the forebody and the disk, and the size of the cavity was varied by moving the disk forward or away from the forebody. The air flow over this body develops vortices inside the cavity and behind the disk; normally these vortices shed, and the flow becomes dynamic. Experimentally it was found that the total drag on this body reaches a minimum when the disk is placed at an optimum location where the vortex formed inside the cavity becomes steady in nature.

Part 3. Fuel-Thermal-Stability Studies

During the course of this program, a series of single-pass heat exchangers designated Near-Isothermal Flowing Test Rigs (NIFTRs) has been employed in experiments designed to understand the response of aviation fuels to thermooxidative stress. These experiments involved measurements of dissolved oxygen (autoxidation) and insolubles (surface and bulk).

Part 4. Pressure-Sensitive-Paint Development and Application

The design criteria for pressure-sensitive paints for aerodynamic applications are: (1) high quantum efficiency, (2) good sensitivity to pressure changes (long lifetimes),

(3) good photostability, (4) ease of application, (5) availability of excitation and detection sources, (6) insensitivity to temperature changes, and (7) rapid response to pressure changes. Understanding the origin of these goals requires a discussion of basic pressure-paint physics. Pressure paints respond to pressure changes through the quenching effect of molecular oxygen. The emission of luminescent molecules (fluorescent or phosphorescent) is quenched by collisional energy transfer with molecular oxygen. Because the oxygen partial concentration varies with pressure, the luminescent quenching is a measure of total pressure.

To date, four candidate pressure paints have been developed and/or evaluated for aerodynamic-flowfield measurements. The paints can be divided into two categories: fluorescent- and phosphorescent-based fluorphores. The fluorescent-based paints employ a fluorescent probe molecule for dynamic-quenching measurements of the partial pressure of oxygen. Fluorescent compounds have short lifetimes but reasonable pressure sensitivity. The

advantages of fluorescent probes over longer-lived phosphorescent probes--decreased sensitivity to temperature, high quantum efficiency, and short lifetimes--make them promising candidates for use with rotating machinery (turbines) in which motion must be stopped. The main disadvantage of fluorescent probe molecules is the reduced sensitivity to pressure of the short lifetimes. Two fluorescent-based paints developed for Wright Laboratory and a paint developed in Russia were studied. The only phosphorescent paint considered for study was an AEDC (Arnold Engineering Development Center) formulation. Good sensitivity to pressure is observed for both the phosphorescent- and the fluorescent-based paints. The Russian paint shows the least sensitivity but was designed to cover a wider pressure range.

TASK NO. 23: Characterization of Gaps and Joints, Boundary Layer and Temperature Recovery

Effects on Fuel Cooled Scramjet Heat Exchanger Thermal Loads

PERIOD OF PERFORMANCE: December 1995 - December 1996

DOLLAR AMOUNT: $191,512

U. D. PRINCIPAL INVESTIGATOR: Richard Neumann

BRIEF DESCRIPTION:

Advanced high speed expendable and man rated engine designs for operations above Mach 4 will require fuel cooled flowpath structures in order to withstand the heat amplification effects created by turbulent boundary layers, gaps and joints required for engine assembly. Accurate knowledge of these heat loads are needed to design fuel cooled heat exchangers to survive nonuniform heat load conditions in rig and engine test environments. The objective of this task was to measure these effects in controlled high Mach wind tunnel tests using instrumented models to simulate the engine flowpath geometric characteristics and flowpath conditions. The successful measurement of these heat loads are intended to reduce the risk of sustaining premature rig and engine heat exchanger failures.

This task effort characterized the surface and flowfield temperatures found in representative combustor to inlet and injector gaps and joints. The effects of supersonic flow and boundary layer transition on wall recovery temperature corrections were also characterized. Existing models were modified to facilitate incorporation of instrumented gap and joint geometrics as well as measurement of upstream boundary layer effects. High response temperature, heat flux and pressure data were measured, reduced and analyzed to support heat exchanger design analysis. Appropriate thermocouple, heat flux gages, data acquisition, rig test hardware and probes were fabricated to support the rig test experiments.

TASK NO. 24 Characterization of Shock Induced Localized Heating in Reacting and Non-reacting Combustor Flows

PERIOD OF PERFORMANCE: March 1996 - January 1997

DOLLAR AMOUNT: $414,708

U. D. PRINCIPAL INVESTIGATOR: Art Lewis

BRIEF DESCRIPTION:

The fluid dynamic performance of scramjet engines rather than the thermal performance of these engines has been stressed in past experiments. While thermal measurements have been made, these measurements have been inadequate to define highly localized phenomena attributed to shock interactions. Those few experiments which have focused on shock interaction phenomena have identified far higher rates of heat transfer than anticipated or projected in design memoranda. As the run durations of these engines increase and as engines composed of flight materials are evaluated, significant localized heating will be observed leading to localized hardware failures. This proposed effort is focused at defining in greater detail the thermal performance of scramjet engine components such that a practical, long-duration scramjet engine can be successfully fabricated and tested.

The objective of this task was to provide data with sufficient depth to support the extended thermal life of a high speed demonstration engine and to provide that data in a form readily usable by design engineers making trade studies of various technical issues that affect that thermal life of the engine.

This task attempted to define the thermal performance of advanced, high speed scramjet engines through analysis, through focused experimentation guided by an improved understanding of previous experimental efforts conducted under the NASP engine program. Based on an understanding of past design efforts and the results of past experimentation, this program focused on those areas of greatest concern in the thermal design of engines for extended performance. This program was conducted through a series of four related subtasks as follows: SUBTASK 1, Instrumentation and subsequent measurements on an existing and previously tested large scale engine hardware in an appropriate test rig; SUBTASK 2, An investigation of shock/boundary interactions in both a perfect and reacting flow; SUBTASK 3, The definition of injector-induced thermal loads on the sidewall of a typical engine flowpath; and SUBTASK 4, Apply the results of these experimental studies into meaningful design trades and trends for application to the anticipated demonstration engine design.

TASK NO. 25: Conduct Field Tests of Advanced Filter Coalescer in Field Environment

PERIOD OF PERFORMANCE: June 1996 - February 1997

DOLLAR AMOUNT: $290,098

SUBCONTRACTOR: C4E, Inc.

SUBCONTRACT PRINCIPAL INVESTIGATOR: Larry Dipoma

U. D. PRINCIPAL INVESTIGATOR: Joseph Swartzbaugh

BRIEF DESCRIPTION:

UDRI and C4E, Inc., recently conducted operational demonstrations of jet fuel thermal stability additives at Air Force and Air National Guard installations. This involved assessing the effectiveness of existing fuel filtration systems at each location; developing a procedure to assure only clean, dry fuel was dispensed to aircraft; and the training of fuels and maintenance of personnel on these procedures. Because of the surfactant nature of the thermal stability additive, special water absorbing (Aquacon) filter elements were used in place of the standard DoD and American Petroleum Institute (API) filter-separator elements downstream of the point of additive injection. C4E consultants trained the base-level personnel on the installation, operation, and quality control monitoring requirements for these new elements.

TASK NO. 26: Surfactant Additives for Improved Low and High Temperature Performance in Jet Fuels

PERIOD OF PERFORMANCE: June 1996 to February 1997

DOLLAR AMOUNT: $90,769

SUBCONTRACTOR: Aspen Systems, Inc.

SUBCONTRACTOR PRINCIPAL INVESTIGATOR: B. Scott Jaynes

BRIEF DESCRIPTION:

Jet fuel is subjected to severe thermal stress during flight because it is used as a heat sink for the thermal energy that is generated by atmospheric friction, engine exhaust, and hydraulic and environmental controls in the aircraft. Fuel decomposition under thermal oxidative conditions leads to deposition of fuel degradation products that clog engine parts and require expensive maintenance. Fuels with substantially improved thermal stability are sought in order to expand the heat sink capability of the fuel and, hence, the performance of the aircraft. The Air Force's JP-8+100 fuel additive package has increased the heat sink capacity roughly 50%, but further increases are required.

Aspen Systems has designed and synthesized a new class of multifunctional additives known as metal deactivating surfactants (MDS). These materials incorporate a metal binding group into a surfactant structure to provide metal deactivation, dispersion and ice inhibition in a single additive. The additives have been deigned specifically for use in fuel using computational modeling to optimize their chemical and physical properties. Thermal oxidative stability testing was performed on one family of MDS additives during the program using Aspen Systems' static thermal oxidation testing apparatus. The MDS materials were found to substantially increase the stability of Jet A as measured by color and deposit formation. In a direct comparison of an MDS additive with the present MDA additive, the MDS treated fuel exhibited substantially less color and deposit formation during thermal oxidation. In low temperature studies, MDS treated JP-8 fuel samples that were moderately wet exhibited reduced water droplet formation compared to untreated JP-8 samples, demonstrating the potential of the MDS materials to serve as ice inhibitors as well.

While results from the MDS additives are promising, further work is required to optimize their performance at both high and low temperatures. Further refinement of the MDS structure should result in a single component additive that outperforms JP-8+100 at high temperature, and simultaneously eliminates or greatly reduces the need for traditional fuel system ice inhibitors.